ELECTRON CAPTURE RATES ON NEUTRON-RICH NUCLEI IN CORE-COLLAPSE SUPERNOVA

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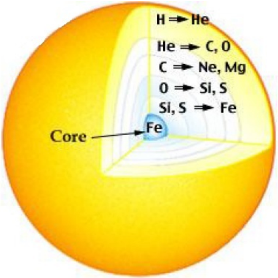
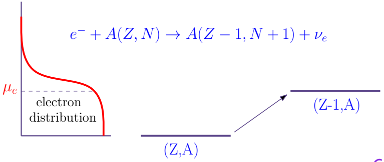




1. At the end of its life a massive star ($M \geq 10 M_\odot$) has an onion like structure.
2. Just before the core-collapse all reactions mediated by the electromagnetic and strong interactions (but not weak interaction!) are in Nuclear Statistical Equilibrium.
3. Electrons form a degenerate gas (keep a pressure due to the Pauli principle).
4. Until $M_{\mathrm{core}} < M_{\mathrm{Ch}} = 1.44(2Y_e)^2 M_\odot$, the gravitation is balanced by the pressure of the degenerate relativistic gas of electrons (Y_e is the number of electrons per one baryon in the star).
5. The equilibrium is unstable since
   - The silicon burning increases the iron core of the star.
   - The electron captures by protons and nuclei (at $\rho \gtrsim 10^9 \mathrm{g/cm}^3$) decrease the pressure of the degenerate electronic gas.
6. When the iron core mass M_{core} exceeds M_{Ch} it collapses.

Electron captures on protons and nuclei

- $(A, Z) + e^- \rightarrow (A, Z-1) + \nu_e$
- $p + e^- \rightarrow n + \nu_e$

At presupernova stage **EC** on nuclei occur under following conditions:

- Temperature: $T = 0.2 - 2.0$ MeV $\approx 2.3 - 23$ GK
- Density: $\rho \gtrsim 10^9$ g/cm^3

EC produce neutrinos which at densities $\rho \lesssim 10^{11} \mathrm{g/cm}^3$ can leave the star unhindered carrying away energy. This is a very efficient cooling mechanism which keeps the entropy of the matter low. As a consequence heavy nuclei survive during the collapse.

EC on iron-group (and heavier) nuclei are very important for the dynamics of gravitational core-collapse of a massive star, triggering a type II supernova explosion. **EC** rates largely determine the mass of the core and thus the fate of the shock wave formed by the supernova explosion.

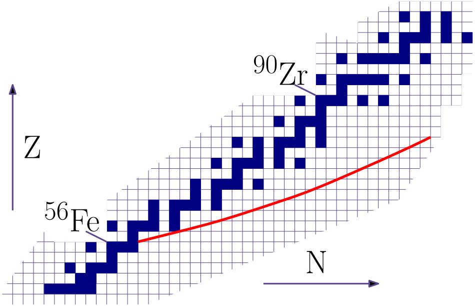
At early stage of collapse **EC** is dominated by Gamow-Teller GT_+ transitions in iron-group nuclei $A = 45 - 65$.

To calculate **EC** cross sections and rates in stellar environment one should know distributions of the spin-isospin transition strengths in nuclear spectra and take into consideration high mean excitation energy of nuclei embedded to hot and dense stellar matter $\langle E \rangle = 10 \div 30$ MeV

Large Scale Shell Model *(K. Langanke, G. Martínez-Pinedo et al.)*: nuclear structure calculations for sd- and pf- shell nuclei with $A \lesssim 65$. Thermal effects are taken into account by state-by-state evaluation of the reaction rate and summing over Boltzmann-weighted, individually determined strengths for the various nuclear states.

Limitations of the LSSM approach

- Axel-Brink hypothesis is used
- First-forbidden transitions cannot be calculated avoiding additional simplifications
- Principle of detailed balance is violated



As the collapse progresses, due to **ECs** the neutronization of the core matter proceeds. A sizeable amount of highly excited neutron-rich nuclei with $A \sim 70-80$ is produced. **The LSSM approach cannot be used in this mass region.**

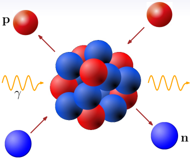
At the first stage of core-collapse studies a role of **ECs** on these nuclides during the collapse was underestimated. It was assumed that the GT_+ transitions in nuclei with the closed neutron pf shell are completely blocked.

To calculate **ECs** on neutron-rich nuclei with $A \gtrsim 70$ and heavier ones **"Shell-Model-Monte-Carlo + RPA" (or hybrid) model** has been elaborated by *K. Langanke, G. Martínez-Pinedo, M. Sampaio, A. Juodagalvis and others.*

The hybrid model has been used for calculations **EC** cross-sections for many neutron-rich nuclides. However, the model exploits not well-founded assumptions and simplifications and moreover is not thermodynamically consistent.

From the thermodynamic point of view the LSSM and "SSMC+RPA" models consider a hot nucleus in a canonical ensemble.

We employ a microscopic thermodynamically consistent approach formulated in a grand-canonical ensemble: Hot nuclei embedded in a stellar matter are considered as a grand canonical ensemble with temperature T and proton and neutron chemical potentials λ_p and λ_n.
(A. Dzhioev, A. Vdovin, V. Yu. Ponomarev, J. Wambach, Phys. At. Nucl. **72** (2009) 1320)



A thermal strength function is introduced as a grand canonical average of transition matrix elements of e.g. $p \to n$ exchange operator $\mathcal{D}_+$ between states i and f in the parent and daughter nuclei

$$S_{\mathcal{D}_+}(E,T) = \sum_{Z,N} \sum_{i,f} S_{if}(\mathcal{D}_+)\delta(E - E_{if})P(i, A_N^Z).$$

$S_{if}(\mathcal{D}_+) = |\langle f, A_{N+1}^{Z-1}|\mathcal{D}_+|i, A_N^Z\rangle|^2$ – a transition strength.

$E_{if} = E_f - E_i + Q = E_e - E_\nu$ – a transition energy which equals the energy difference of the incoming electron and the outgoing neutrino; Q – the mass difference of daughter and parent nuclei.

$P(i, A_N^Z)$ – a probability to find the initial state i in the grand canonical ensemble.

To calculate the thermal strength function $S_{\mathcal{D}_+}(E,T)$ we apply the formalism of Thermo Field Dynamics (TFD)

TFD (H. Umezawa and coworkers) – a real-time formalism allowing to consider thermal effects in quantum field theory and non-relativistic many-body theories.

- *Basics of Thermo Field Dynamics*
  - Doubling nuclear degrees of freedom: $|nlj\rangle \otimes \widetilde{|nlj\rangle}$, $H|\Psi_k\rangle = E_k|\Psi_k\rangle$, $\widetilde{H}\widetilde{|\Psi_k\rangle} = E_k\widetilde{|\Psi_k\rangle}$
  - Thermal Hamiltonian: $\mathcal{H} = H - \widetilde{H}$
  - Thermal vacuum: $\langle 0(T)|A|0(T)\rangle = \langle\langle A\rangle\rangle$; it has to satisfy conditions $\mathcal{H}|0(T)\rangle = 0$ and $A|0(T)\rangle = e^{\mathcal{H}/2T}\widetilde{A}^\dagger|0(T)\rangle$.
- *Thermal quasiparticle RPA*
  - The nuclear Hamiltonian: $H = H_{MF} + H_{BCS} + H_{ph}$;
  - Thermal quasiparticles: $\mathcal{H}_{MF+BCS} = \sum_j \varepsilon_j(\beta_j^\dagger\beta_j - \widetilde{\beta}_j^\dagger\widetilde{\beta}_j)$;
  - Thermal phonons: $\mathcal{H}_{TQRPA} = \sum_k \omega_k(Q_k^\dagger Q_k - \widetilde{Q}_k^\dagger\widetilde{Q}_k)$.

Important:
$\mathcal{H}_{TQRPA}Q_k^\dagger|0(T)\rangle = \omega_k Q_k^\dagger|0(T)\rangle, \mathcal{H}_{TQRPA}\widetilde{Q}_k^\dagger|0(T)\rangle = -\omega_k\widetilde{Q}_k^\dagger|0(T)\rangle$

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The TFD strength function of charge-exchange operator $S_{\mathcal{D}}(E,T)$ is

$$S_{\mathcal{D}}(E,T) = \sum_i S_{\mathcal{D}}(\mathcal{E}_i)\delta(E-\mathcal{E}_i) + \widetilde{S}_{\mathcal{D}}(\mathcal{E}_i)\delta(E+\mathcal{E}_i)$$

Excitation strength: $S_{\mathcal{D}}(\mathcal{E}_i) = \left|\langle \mathbf{0(T)}|Q_i\|\mathcal{D}\|\mathbf{0(T)}\rangle\right|^2$

Transition energy: $\mathcal{E}_i = \omega_i + (\lambda_n - \lambda_p) + \Delta\mathrm{M}_{np}$

De-excitation strength: $\widetilde{S}_{\mathcal{D}}(\widetilde{\mathcal{E}}_i) = \left|\langle \mathbf{0(T)}|\widetilde{Q}_i\|\mathcal{D}\|\mathbf{0(T)}\rangle\right|^2$

Transition energy: $\widetilde{\mathcal{E}}_i = -\omega_i + (\lambda_n - \lambda_p) + \Delta\mathrm{M}_{np}$

$\lambda_n - \lambda_p$ is the difference of neutron and proton chemical potentials;
$\Delta\mathrm{M}_{np}$= 1.29 MeV – the mass difference of $neutron$ and $proton$.

The detailed balance principle and Ikeda sum rule (for the bare operators $\mathcal{D} = \mathrm{GT}_{\pm}$) are fulfilled automatically

$$\widetilde{S}_i^{(\mp)} = \exp\left(-\frac{\omega_i}{T}\right) S_i^{(\pm)}$$

$$\sum_i \left[S_{GT_-}(\omega_i) + \widetilde{S}_{GT_-}(\omega_i)\right] - \sum_i \left[S_{GT_+}(\omega_i) + \widetilde{S}_{GT_+}(\omega_i)\right] = 3(N-Z).$$

Knowing $S_{\mathcal{D}}(E,T)$ one can compute **EC** cross sections and rates

$$\sigma(E_e,T) \sim \int_0^{E_e} S_{\mathcal{D}}(E,T) F(Z,E_e)(E-E_e)^2 dE;$$
$$\lambda(T) \sim \int_0^{\infty} \sigma(E_e,T) E_e p_e f(E_e,T) dE_e,$$

where $F(Z,E_e)$ accounts for the Coulomb distortion of the electron wave function and $f(E_e,T)$ is the electron distribution function at different temperatures and density.
Strength functions $S_{\mathcal{D}}(E,T)$ for GT_- and GT_+ transitions are related by the principle of detailed balance

$$S_{\mathsf{GT}_-}(-E,T) = S_{\mathsf{GT}_+}(E,T)\exp\Big\{-\frac{E-(\lambda_n-\lambda_p+\Delta \mathsf{M}_{np})}{T}\Big\}$$

Transition operators (non-relativistic case)

- Allowed 0^+ and 1^+ transition operators:

$$\mathcal{D}_+ = (g_{_V} + g^*_{_A}\boldsymbol{\sigma})\tau_+$$

- First-forbidden 0^-, 1^- and 2^- transition operators ($\hbar = c = 1$):

$$\mathcal{D}_+(0^-) = g^*_{_A}\left[\frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{m} + \frac{\alpha Z}{2R} i\boldsymbol{\sigma}\cdot\boldsymbol{r}\right]\tau_+,$$

$$\mathcal{D}_+(1^-) = \left[g_{_V}\frac{\boldsymbol{p}}{m} - \frac{\alpha Z}{2R}\left(g^*_{_A}\boldsymbol{\sigma}\times\boldsymbol{r} - ig_{_V}\boldsymbol{r}\right)\right]\tau_+,$$

$$\mathcal{D}_+(2^-) = ig^*_{_A}\left(\frac{p_e^2 + q_\nu^2}{3}\right)^{1/2}[\ \boldsymbol{\sigma}\cdot\boldsymbol{r}\ ]_{2\mu}\tau_+.$$

Self-consistent nuclear Hamiltonian based on Skyrme interaction.

- Skyrme interaction:

$$V(\mathbf{r}_1, \mathbf{r}_2) = t_0(1 + x_0 P_\sigma)\delta(\boldsymbol{r}) + \frac{1}{2}t_1(1 + x_1 P_\sigma)(\mathbf{k}^2\delta(\mathbf{r}) + \delta(\mathbf{r})\mathbf{k}'^2)$$
$$+ t_2(1 + x_2 P_\sigma)\mathbf{k}'\delta(\mathbf{r})\mathbf{k} + \frac{1}{6}t_3\rho^\alpha(\mathbf{R})(1 + x_3 P_\sigma)\delta(\mathbf{r})$$
$$+ iW(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)[\mathbf{k}' \times \delta(\mathbf{r})\mathbf{k}],$$

  where $\boldsymbol{r} = \boldsymbol{r}_1 - \boldsymbol{r}_2$, $\boldsymbol{k} = (\boldsymbol{\nabla}_1 - \boldsymbol{\nabla}_2)/2i$, $\boldsymbol{k}' = -(\boldsymbol{\nabla}_1 - \boldsymbol{\nabla}_2)/2i$, $\boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2$.

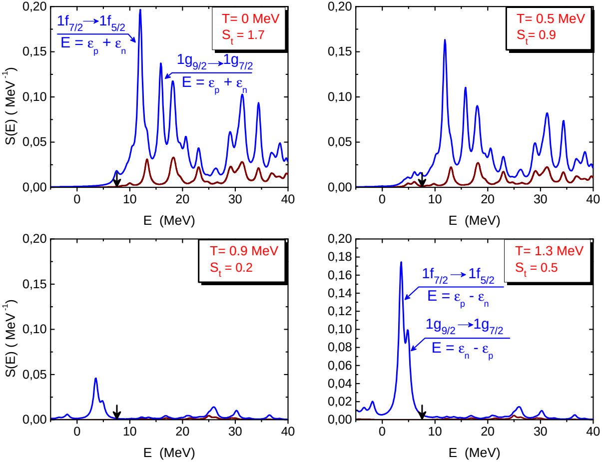
- Hartree-Fock states:

$$\frac{\delta}{\delta\phi_i}\Big(E - \sum_i e_i \int |\phi_i(\mathbf{r})|^2 d\mathbf{r}\Big) = 0.$$

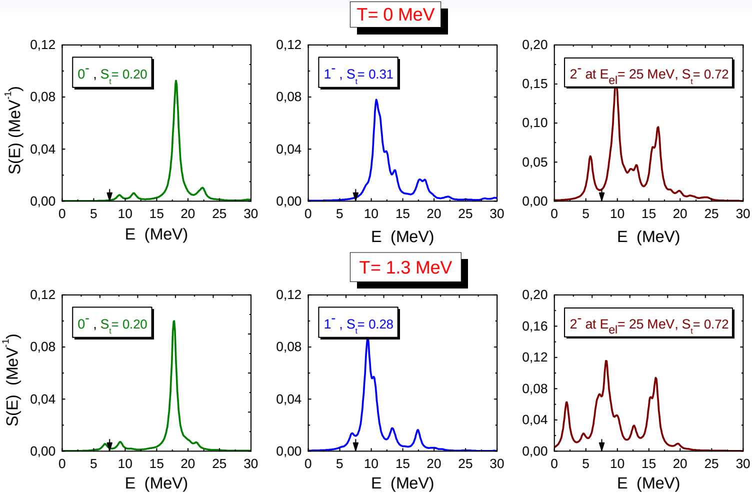
- Landau-Migdal interaction in the spin-isospin channel

$$H_{ph} = \frac{\pi^2\hbar^2}{2k_F m^*}[F_0' + G_0'\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2]\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\delta(\boldsymbol{r})$$

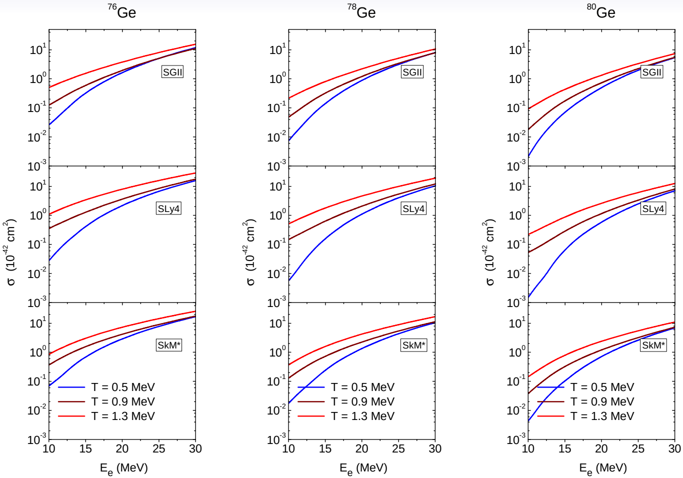
- Calculations are performed with parameterizations SGII, SLy4, SkM*



Temperature evolution of the strength functions S(E) of allowed $p \rightarrow n$ transitions on ^{76}Ge. E – the transition energy, S_t – the total transition strength. The arrow indicates the zero-temperature reaction threshold $Q_{EC}(^{76}Ge) = 7.52$ MeV.
Blue curves – the strength function of 1^+ (GT_+) transitions. Brown curves – the strength function of 0^+ transitions. Calculations are performed with SGII interaction.

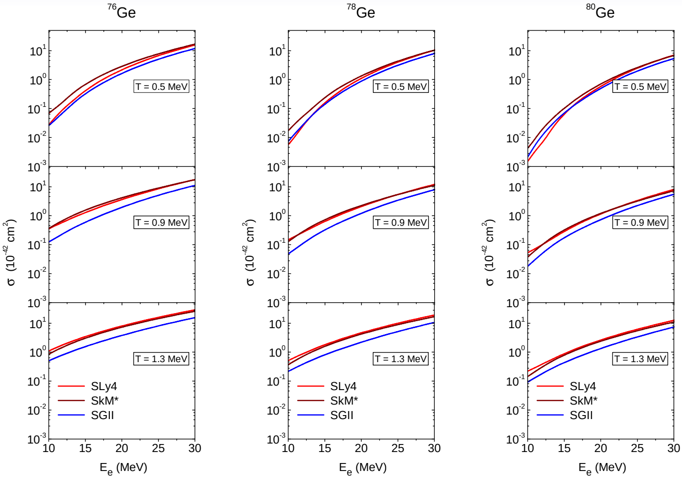


Strength functions of first-forbidden $p \to n$ transitions with $J^\pi = 0^-, 1^-, 2^-$ on ^{76}Ge at T=0 and T=1.3 MeV. E – the transition energy, S_t – the total transition strength. The arrow indicates the zero-temperature reaction threshold. Calculations are performed with SGII interaction.



EC cross sections σ calculated within the TQRPA for ^{76,78,80}Ge isotopes as functions of incoming electron energy E_e. Both allowed and first-forbidden transitions are taken into account.

Each panel shows the temperature evolution of **EC** cross sections for the selected Skyrme force: SGII (upper panels), or SLy4 (middle panels), or SkM* (lower panels).



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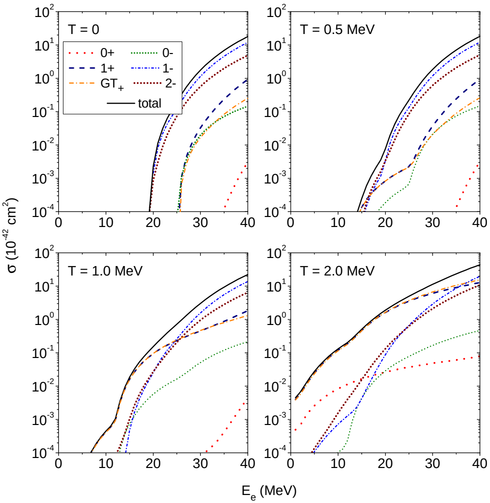
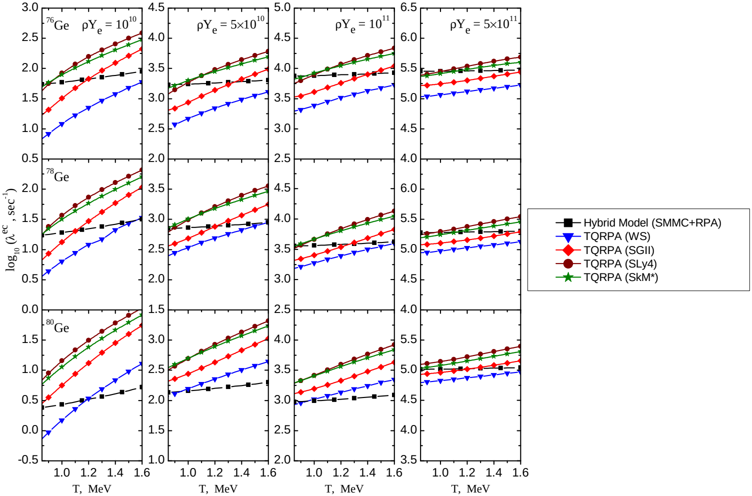
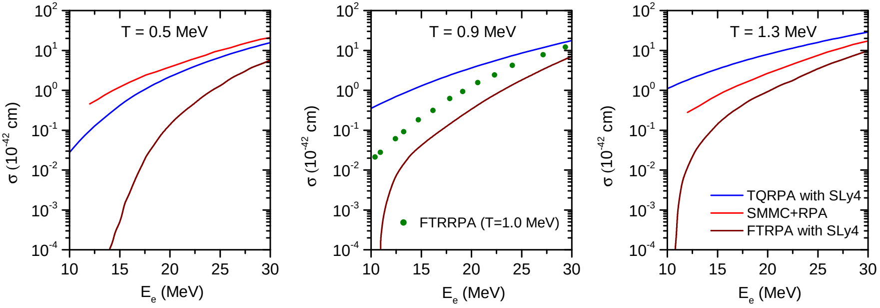
Each panel shows **EC** cross sections calculated with Skyrme forces SGII, SLy4, and SkM* at given T.



EC cross sections σ on ^{78}Ni for different multipoles as a functions of electron energy E_e at different temperatures T. Calculations are performed for SkM* interaction.



Electron capture rates λ^{ec} on ^{76}Ge (upper panels), ^{78}Ge (middle panels) and ^{80}Ge (lower panels) as functions of temperature T at selected values of density $\rho Y_e (g/cm^3)$. The results of the Hybrid model (black squares) and QPM-TQRPA (blue triangles) are also displayed.



EC cross sections σ on ^{76}Ge as function of incoming electron energy E_e calculated within different approaches.

Blue curves: Present calculations (TQRPA with Skyrme interaction SLy4)

Brown curves: FT-RPA with Skyrme force SLy4 (A.F. Fantina et al. PRC **86** (2012) 035805)

Red curves: SMMC+RPA or Hybrid model (K. Langanke et al., PRC **63** (2001) 032801(R)

Green dots (middle panel): FT-relativistic-RPA (Y.F. Niu et al., PRC **83** (2011) 045807)

- The thermodynamically consistent Thermal QRPA approach combined with the self-consistent Skyrme-HF scheme is developed. The approach can be widely used in calculations of weak interaction mediated process rates in stellar matter without limitations of masses and excitation energies of involved nuclei.
- Using the ^{76,78,80}Ge nuclides as an example, electron captures on hot neutron-rich nuclei embedded in stellar matter under pre-supernova conditions are studied. Our Skyrme-TQRPA approach predicts the stronger thermal enhancement of **EC** cross sections and rates than other approaches. This is due to thermodynamically consistent consideration of the de-excitation processes on hot nuclei that sizeably enhance the **EC** cross sections at low energies of captured electrons.

THANK YOU FOR ATTENTION